JOURNAL OF AIRCRAFT
Vol. 38, No. 4, July–August 2001

Multidisciplinary Design of Vehicle Structures with Improved Roll Maneuverability—Transonic Regime

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The objective of this research is the preliminary design of aircraft structures for improved steady-state roll performance in the transonic regime. The control surface effectiveness (a parameter that indicates the relative rolling power produced by an aileron of a flexible aircraft with respect to the rigid aircraft) is employed for quantifying the roll performance. Control surface effectiveness is evaluated by iteratively solving the antisymmetric trim equation on roll rate. Each iteration of the trim equation necessitates the computation of nonlinear airloads. To make the multidisciplinary design optimization computationally practical, the transonic small disturbance (TSD) theory is used for the aerodynamic analysis. Transonic loads including shock effects are captured by employing the TSD theory for which the CAP–TSD program is used. For design optimization, a nongradient-based method is adopted. Control surface effectiveness variation with respect to the statistically significant structural variables (skins, spars, ribs, and posts) is approximated using the response surface method. Multidisciplinary optimization for minimum weight, with control effectiveness, stress, displacement, and frequency constraints, is performed.

Introduction

MULTIDISCIPLINARY design of aircraft structures subjected to various performance criteria such as lift, rolling moment, stresses, frequency, and displacement in the subsonic and supersonic regime is a common practice with the availability of tools such as ASTROS[1] and MSC/NASTRAN.[2] The major simplifying issue making multidisciplinary design optimization (MDO) possible is the validity of linear assumptions of the aerodynamics involved in the subsonic and supersonic region. However, its extension into the transonic region is not straightforward because shock waves significantly effect the flowfield, thus making the aerodynamics nonlinear. In such cases, the linear aerodynamic loads are replaced with maneuver loads calculated from databases of loads obtained from wind-tunnel testing or from computational fluid dynamics (CFD) analyses. Until recently, little effort has been expended to include nonlinear aerodynamic loads in the preliminary structural design environment due to the large computational cost associated with the solution of nonlinear equations. However, with the advances in nonlinear aerodynamic flow solvers and computer hardware, nonlinear airloads can now be calculated at a reasonable computational cost, provided efficient solution procedures are employed. Furthermore, to aggravate the computational cost, many such costly analyses are required during design. Hence, efficient design procedures are to be adopted to make the solution computationally practical for preliminary design. The focus of this research is to develop a suitable design procedure along with selecting an efficient nonlinear aerodynamic analysis for performing MDO of aircraft structures.

Aeroelastic analysis of flexible aircraft in the transonic regime is a relatively recent endeavor. In 1990, Bharadvaj[3] predicted the steady and unsteady transonic airloads due to control surface deflection. The transonic small disturbance (TSD) theory was employed, and aircraft flexibility was not taken into account. Recently, a study was undertaken by Anderson et al.[4] that examined the aeroelastic effects due to control surface deflections in transonic flow including flexibility effects. The TSD theory was employed for the prediction of pressure distributions and static aeroelastic phenomena. Rolling moments and reversal points were examined for varying Mach numbers. It was discovered that the inclusion of nonlinear aerodynamics significantly affected pressure distributions and static aeroelastic behavior. This fact is supported in this research, where it is found that linear aerodynamics in the transonic regime predicts nonconservatively high rolling efficiencies.

As a precursor to design optimization, many algorithms need analytical gradients of performance measures for computing the search directions. Kapania et al.[5] calculated sensitivities of flutter response with configurational parameters such as aspect ratio, wing area, taper ratio, and sweep. In that study, aerodynamic loads are modeled using state-space representation, and aerodynamic forces and moments are approximated using closed-form indicial response functions. Kolonay et al.[6] developed sensitivities for flutter performance with respect to structural sizing variables using TSD aerodynamics. In structural optimization with aerodynamic loads provided by CFD schemes, an interesting approach is proposed by Raveh and Karpel.[7] In that approach, several aeroelastic trim corrections and optimization runs are performed during the process of flowfield convergence (CFD iterations are prematurely stopped), such that the aerodynamic loads and structural design are converged simultaneously.

In structural optimization, when sensitivity information is not available and the function evaluation is computationally expensive, using the response surface method for approximating the dependent variable as a function of independent variables is a popular choice. Careful application of the response surface method by judicious selection of design points, independent variables, and ranges of independent variables leads to a reasonably accurate approximation. In this research, a nongradient-based approach involving response surface approximations is adopted. The transonic design features along with the computational cost issues involved are discussed in the next section.

Design and Computational Issues Involved

Efficient and accurate prediction of nonlinear airloads is necessary for designing the aircraft in the transonic regime. The flow

Received 20 November 1999; revision received 25 October 2000; accepted for publication 11 November 2000. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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in the transonic regime is a mixture of subsonic and supersonic flow with embedded shocks. The governing transonic aerodynamics equations are highly nonlinear and are computationally expensive to solve. The aerodynamic nonlinearities have a significant impact on the aeroelastic quantities and on the design and, thus, have to be taken into account. Full fledged Euler or Navier–Stokes solution methods can not be used in preliminary design due to the enormous cost involved. If viscous effects are also taken into account in the aerodynamic equations, the computation cost is still more expensive. However, according to a study by Andersen et al.,[8] it was found that the inclusion of viscous effects reduces the magnitudes of the aerodynamic loads and, hence, the elimination of viscosity effects leads to a more conservative design without expensive viscous analysis in the preliminary design.

Coupled structural and aerodynamic equations are solved to compute lift or rolling moment by steady aeroelastic analysis. In the transonic regime, where aerodynamics is nonlinear, the solution for coupled equations becomes a complex process. Furthermore, with the structural model consisting of thousands of degrees of freedom, the structural equations take significant computational time if suitable modal reduction methods are not employed. The iterative solution of coupled aerodynamic and structural equations is referred to as CAP–TSD static aeroelastic analysis in this paper.

For the roll maneuverability computation, the antisymmetric trim equation is solved. This is done by employing an iterative method that requires the stability derivative information at each iteration. These stability derivatives are calculated using the finite difference method, which demands the CAP–TSD static aeroelastic analysis be repeated twice for each iteration. (This is the most computationally expensive loop of the analysis.) The trim analysis that includes CAP–TSD static aeroelastic analyses is referred to as CAP–TSD trim analysis in Fig. 1.

If an angle of attack is present along with the control surface deflection, the nonlinearities in the governing transonic aerodynamic

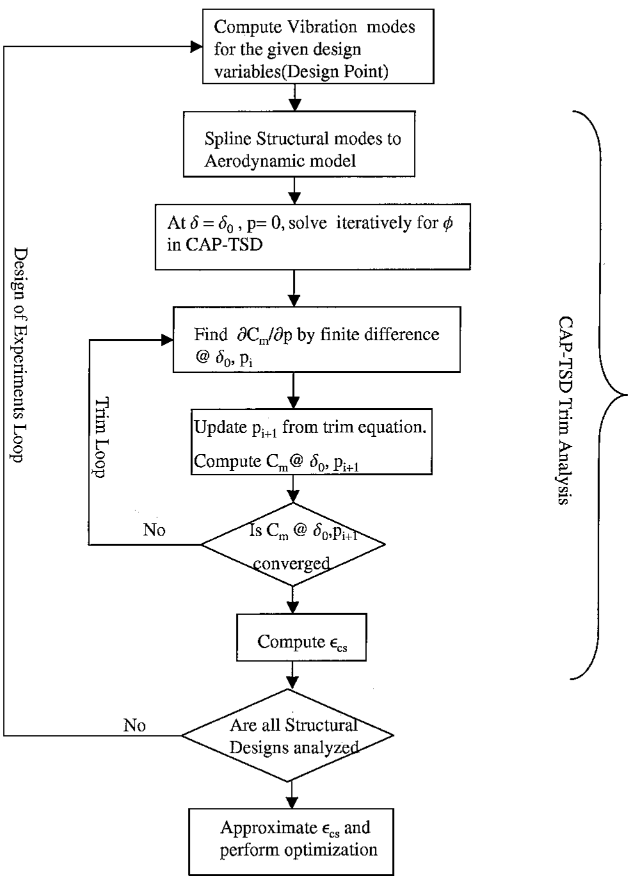

Fig. 1 Effectiveness ϵ_{cs} computation and nongradient-based optimization.

equations are greatly amplified. Unlike linear aerodynamics, the individual effects due to control surface deflection, angle of attack, and roll rate cannot be superimposed. Thus, all of the configurational effects have to be taken into account simultaneously, which induces high nonlinearities. A limitation of the TSD theory is that it is no longer valid if high nonlinearities (such as those imposed during extreme flight conditions) are present. In this research, angle-of-attack effects have not been included.

The design of the aircraft wing involves both configurational design (such as deciding the number of spars, the number of ribs, the sweep angle, and the aspect ratio) as well as structural sizing (such as deciding the thickness of skins, spars, ribs, and the cross-sectional areas of posts). Configurational design and structural sizing are done independently with structural sizing designed for the optimum configuration. To perform configuration design using optimization techniques, sensitivities of response quantities such as stress, displacement, frequency, lift, rolling moment, and drag are needed with respect to configurational parameters. This information is difficult to determine; therefore, nongradient-based methods such as the response surface method could be used. Li et al.[9] investigated the response surface based configuration design procedure. However, in the present paper, only structural sizing is considered. For structural sizing as well, the sensitivities of static aeroelastic response quantities with respect to structural thickness is difficult to compute due to iteratively solved coupled structural and aerodynamic equations.

Typically, for structural sizing, the number of design variables is large (in hundreds) because each element's dimensions could potentially be a design variable. However, for the purposes of manufacturability and symmetry, and for making the optimization problem tractable, the physical variables could be linked to a few global or linked variables. A major disadvantage of nongradient methods is that the number of analyses needed at different design points in the design space increases exponentially as the number of design variables increase. Because each analyses is expensive in itself, not many analyses could be performed because it would generally outweigh the computer resources available. Methods to reduce the number of design variables and the number of experiments needed must, therefore, be investigated. Finally, the design is in the preliminary design environment where a number of alternative designs must be evaluated, and suitable modifications (such as changing the location and size of control surfaces) have to be incorporated. Therefore, it demands a less expensive design procedure because the whole design process has to be repeated for several structures.

Design Methodology

The design for roll maneuverability involves computation of control surface effectiveness for different structural dimensions. The control surface effectiveness calculation requires solution of nonlinear antisymmetric trim equation, which in turn requires stability derivatives (rolling moment with respect to control surface deflection and rolling moment with respect to roll rate). Calculation of rolling moment is necessary for obtaining the stability derivatives, and this is done by iteratively solving the coupled structural and nonlinear aerodynamic equations for a converged steady flow solution. The aerodynamic and static aeroelastic analysis procedures involved are described next.

Aerodynamic Analysis

The governing nonlinear transonic aerodynamic equations must be solved for capturing sonic shocks. Although use of CFD techniques to solve the full-fledged Euler/Navier–Stokes (ENS) equations has the advantage of accuracy and applicability for high nonlinearities, it is accompanied by many challenges. The main issue is the high computational cost associated with it. This difficulty is amplified in the structural design process where the airloads must be evaluated several times during the design process. The evaluation of stability derivatives using the finite difference method and iterative solution procedure for nonlinear antisymmetric trim analyses requires a number of ENS simulations, which is not practical in the preliminary design stage. Furthermore, the CFD–ENS schemes have to be integrated with structural analysis procedures for including the flexibility effects.

The aerodynamic equations are simplified using the TSD assumptions. Although TSD assumptions result in one of the simplest nonlinear equations for aerodynamics, it is capable of determining the strength and location of weak shocks. Moreover, because of its efficiency and relatively less computational cost compared to ENS solutions, it is considered appropriate for preliminary design environment. The virtue of the TSD theory is obtaining the order of magnitude of aerodynamic pressures. The TSD solver, as implemented in CAP–TSD,[10] is considered to be one of the fastest algorithms and has fulfilled the accuracy requirements[11] for preliminary design. It uses the efficient approximate factorization algorithm that consists of a Newton linearization procedure coupled with the internal iteration technique.[12] CAP–TSD also takes into account flexibility effects by solving coupled structural and aerodynamic equations. Additionally, it uses a modal approach where the whole structure with thousands of degrees of freedom deformation is approximated by the first few structural modes. Although CAP–TSD was developed to solve a dynamic aeroelastic flutter problem, it can be tailored to solve a static aeroelastic problem by using a high structural damping and taking the converged solution.

In the TSD theory, the flow is assumed to be governed by a general frequency modified TSD potential equation, which is written in conservation law form as

$$\frac{\partial f_0}{\partial t} + \frac{\partial f_1}{\partial x} + \frac{\partial f_2}{\partial y} + \frac{\partial f_3}{\partial z} = 0 \tag{1}$$

where

$$f_0 = -A\phi_t - B\phi_x \tag{2}$$

$$f_1 = E\phi_x + F\phi_x^2 + G\phi_y^2 \tag{3}$$

$$f_2 = \phi_y + H\phi_x\phi_y \tag{4}$$

$$f_3 = \phi_z \tag{5}$$

The coefficients A, B, and E are defined as

$$A = M_\infty^2, \qquad B = 2M_\infty^2, \qquad E = 1 - M_\infty^2 \tag{6}$$

where M_∞ is the far-field Mach number and ϕ is the velocity potential.

F, G, and H, are specified depending on the assumptions used in deriving the TSD equation. For nonlinear analyses, the coefficients are

$$F = -\tfrac{1}{2}(\gamma + 1)M_\infty^2, \qquad G = -\tfrac{1}{2}(\gamma - 3)M_\infty^2$$
$$H = -(\gamma - 1)M_\infty^2 \tag{7}$$

and for linear analyses,

$$F = 0, \qquad G = 0, \qquad H = 0 \tag{8}$$

In the preceding equations, γ is the ratio of specific heats (1.4 for air). For steady flow calculations, after Newton linearization, internal iterations are not used because time accuracy is not necessary when marching to steady state. The solution of the TSD equation is the converged steady-state velocity potentials, from which aerodynamic pressures are calculated. From the aerodynamic pressures, total lift and rolling moment are calculated.

Static Aeroelastic Analysis

The static aeroelastic analysis in the transonic region is quite different from linear static analysis because of the nonlinearity of the aerodynamic loads. The solution of coupled static aeroelastic equations and aerodynamic equations is an iterative process. Additionally, the trim analysis is also a nonlinear iterative process due to nonlinear aerodynamics.

The matrix equation of static aeroelastic analysis in a general form is given by

$$K\boldsymbol{u} = F[\boldsymbol{u}, \delta] \tag{9}$$

where K is the structural stiffness matrix, $\boldsymbol{u}$ is the displacement vector, and δ are the configuration variables such as angle of attack, control surface deflection, pitch rate, and roll rate. $F(\boldsymbol{u}, \delta)$ is the aerodynamic load, which is a function of the structural deformation and rigid configuration parameters. This is solved by the iterative scheme

$$K\boldsymbol{u}^{n+1} = F[(\boldsymbol{u})^n, \delta^n] \tag{10}$$

For solving the preceding equation, the aerodynamic loads from the aerodynamic model must be splined to the structural model, and the structural deformations must be splined from the structural model to the aerodynamic model. Additionally, for the CAP–TSD analysis, the streamwise slopes of mode shapes are also required.

Solving the coupled equations in physical coordinates is not practical due to the large number of degrees of freedom involved in the structural and aerodynamic models. The generalized coordinates method, where a first few structural modes are used to approximate the structural deflections, is significantly more efficient. Using modal coordinates, a large number of structural degrees of freedom (in tens of thousands) can be reduced to a few (not more than 50) resulting in significant computational savings.[13]

Control surface effectiveness is defined as the flexible to rigid ratio of the rolling moment stability derivative produced by a control surface deflection at a given flight condition. Control surface effectiveness ϵ_{cs} is given by

$$\epsilon_{cs} = \frac{C_{m_{\delta_{\text{flexible}}}}}{C_{m_{\delta_{\text{rigid}}}}} \tag{11}$$

For a rigid aircraft, $\epsilon_{cs} = 1$; when reversal occurs, $\epsilon_{cs} = 0$. $C_{m_{\delta_{\text{rigid}}}}$ is dependent on aerodynamic planform but is independent of structural deformations. The calculation of ϵ_{cs} requires only one antisymmetric trim analysis for computing $C_{m_{\delta_{\text{flexible}}}}$ for the given structural sizes because $C_{m_{\delta_{\text{rigid}}}}$ is constant for all structural sizes.

The nonlinear trim analysis equation that is to be satisfied for the computation of control surface effectiveness is given by

$$\int_0^{\delta_0} C_{m_\delta}\,\mathrm{d}\delta + \int_0^{p} C_{m_p}\,\mathrm{d}p = 0 \tag{12}$$

where C_{m_δ} is the coefficient of rolling moment with control surface deflection, δ_0 is the fixed control surface deflection, C_{m_p} is the coefficient of rolling moment with roll rate, and p is the roll rate. C_{m_δ} has a units of per degree and C_{m_p} per degree per second.

Note that in the nonlinear aerodynamics regime, both C_{m_δ} and C_{m_p} are functions of both p and δ. Finite difference (first-order forward difference formula) is used to calculate both C_{m_δ} at $\delta = \delta_0$ and C_{m_p} during each iteration at that particular roll rate (initial roll rate is zero). The roll rate is recursively computed until convergence of the trim equation by

$$p_n = p_{n-1} + \Delta p_n = -\frac{C_{m_\delta}\big|_{n-1} \times \delta}{C_{m_p}\big|_{n-1}} \tag{13}$$

Thus, the computation of ϵ_{cs} involves an iterative solution of the trim equation, which further involves multiple nonlinear TSD equation solutions to compute the stability derivatives. The flow chart in Fig. 1 shows the computation of ϵ_{cs} along with the design of experiments loop.

Before proceeding with the design of structure for improved ϵ_{cs}, aerodynamic model specification in CAP–TSD and integration of structural and aerodynamic analysis need to be checked. The next section discusses the validation procedure used for the computation of ϵ_{cs}.

Validation of Control Surface Effectiveness Calculation

For validating ϵ_{cs} computation, linear analysis is done in the subsonic region using the procedure mentioned before in CAP–TSD and is compared against the linear-aerodynamics-based ASTROS. An analysis in the transonic regime using CAP–TSD is not comparable to the ASTROS analysis due to presence of aerodynamic nonlinearities that significantly affect ϵ_{cs}. A linear analysis is done in CAP–TSD by setting the coefficients of the TSD equation to $F = 0$, $G = 0$, and $H = 0$. The trim analysis for a subsonic Mach number should converge in one iteration because the stability derivatives remain constant at any value of configurational variables such as roll rate and control surface deflection. Similar results from both ASTROS and CAP–TSD for ϵ_{cs} validates 1) the aerodynamic model specification in CAP–TSD, 2) the number of modes selected for approximating the structural deformations, 3) proper data transfer between ASTROS and CAP–TSD, and 4) the linear CAP–TSD analysis and trim analysis used in CAP–TSD.

Instead of comparing a single value of ϵ_{cs} calculated using both programs (ASTROS and CAP–TSD), the variation of ϵ_{cs} with dynamic pressures ranging from zero to reversal is calculated. The reversal dynamic pressure can be found in ASTROS by performing a series of antisymmetric trim analysis with increasing dynamic pressures. In all of the analyses, the constant sea level density is maintained while matching the velocity with dynamic pressure. In this research the subsonic analysis is performed at 0.8 Mach.

Design of Experiments Methodology

Nongradient-based approximations are used to approximate the control surface effectiveness variation with respect to the structural thicknesses. Design of experiments (DOE) methodology uses statistical techniques, especially regression methods, to approximate the variation of a response quantity with respect to the independent variables. In this context, the experiment is to determine ϵ_{cs} for particular structural member thicknesses. From a list of possibly influential independent variables (linked design variables), significant variables are chosen by conducting experiments at preselected points using the fractional factorial design method.[14] Once the statistically insignificant variables are eliminated, a suitable number of the design points in the independent variable space for conducting the experiments are chosen. In this research, this is done using D-optimality criteria. Finally, after the experiments are conducted, a quadratic response surface is fitted using the least-squares method to approximate ϵ_{cs}.

The detailed stages of DOE methodology are discussed in the next three subsections.

Fractional Factorial Design

Fractional factorial design is used to select the statistically significant variables. It is a two-level design, in which two levels (high and low) are selected for each variable. As the number of independent variables increase, for example, for k variables, the number of experiments needed are 2^k, which is a large number. Fortunately, there tends to be decreasing importance of the interaction effects in the polynomial as the order of the interactions increases; that is, main effects tend to be larger than two-factor interactions, which are in turn larger than three-factor interactions and so on. Thus, if the experimenter can reasonably assume that certain higher-order interactions are negligible, then information on the main effects and low-order interactions are obtained by running only a fraction of the complete factorial experiment. Depending on the number of design variables, cost of each analysis, and accuracy required, a suitable fractional factorial design is selected.[15]

After conducting CAP–TSD analyses at all of the selected points and finding the control surface effectiveness values, a linear first-order regression model of the form

$$\widehat{\epsilon_{cs}} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i \tag{14}$$

is fit. To decide whether a particular variable is statistically significant or not, a null hypothesis of $\hat{\beta}_i = 0$ is tested against $\hat{\beta}_i \neq 0$ with a 95% (a chosen percentage) confidence level using the F statistic (which is the ratio of the total regression mean square to the residual mean square). If the value of the calculated F statistic is larger than the corresponding 95% value, then the variable is significant.

D-Optimality

After eliminating statistically insignificant variables and before conducting the response surface approximation of control surface effectiveness, the points in the design space where the experiments need to be run are determined. The selection of design points has a significant influence on the accuracy and cost of computing the response surface.

The best of the computer-generated designs use optimal design theory, and the most popular optimal design is the D-optimality. It is based on the notion that the experimental design should be chosen from a given set of all possible design points to minimize the variance of parameter estimates β. Finding D-optimal points involves an iterative search technique for selecting the appropriate design points.

Response Surface Approximation

The response surface method is an approach of constructing global approximations to system behavior based on the experiments evaluated at various points in the design space.

The second-order response surface model used in this research is of the form

$$\eta = \hat{\beta}_0 + \sum_{j=1}^{k} \hat{\beta}_j x_j + \sum_{i=1}^{k} \sum_{j=1}^{k} \hat{\beta}_{ij} x_i x_j \tag{15}$$

where η is the dependent function to be approximated and x are the independent variables.

The least-square estimates of $\hat{\beta}$ is found by minimizing the sum of squares of the errors using the least-squares method. This results in

$$\hat{\beta} = (X^T X)^{-1} X^T y \tag{16}$$

where y is the function value at the design points.

For k variables, the second-order model has $p = (k+1)(k+2)/2$ model terms. The number of experimental points should be at least $p + 10$. The significance of the overall regression is computed using the F statistic, which must exceed the chosen test percentage point by at least a factor of four for the model to be used for prediction.[16]

Optimization

By the approximation of ϵ_{cs}, a closed-form equation is obtained in terms of structural size variables. MDO is performed for minimizing weight with constraints from various disciplines such as stress, displacement, frequency, and control surface effectiveness. The values of stress, displacement, and frequency are obtained using finite element analysis, and their sensitivities with structural design variables are calculated analytically. ASTROS is used both for finite element analysis and design optimization. For optimization ASTROS internally calls DOT.[16] Approximate closed-form ϵ_{cs} is defined as a synthetic constraint in ASTROS. Sensitivity of control surface effectiveness is calculated using the closed-form equation. Comparison of optimum design obtained using linear aerodynamics in the transonic regime vs that found using nonlinear aerodynamics is performed. The comparison is with reference to various parameters such as weight, material distribution, control surface effectiveness values, and reversal dynamic pressure. Actual ϵ_{cs} and reversal dynamic pressures are computed at the optimum design point by performing CAP–TSD analyses.

Structural Design Example

Implementation

Because the aeroelastic equations are solved using generalized modal coordinates, eigenvalues, eigenvectors, and generalized mass are needed for the structural model. To obtain these, a modal analysis is performed in ASTROS. The number of mode shapes for approximating the structural deflections depends on the complexity of the structure. Splining of structural mode shapes to the aerodynamic model is performed using the infinite plate spline method of ASTROS. The MAPOL sequence of ASTROS is modified to obtain the splined modes and slopes of modes in the streamwise direction on the aerodynamic model. The same CAP–TSD aerodynamic model (corresponding to the physical wing) is used in ASTROS also, to obtain the splining matrices. The mode shapes on the structural and aerodynamic models are visualized for splining errors using MIDAS,[17] a graphical interface for creating and visualizing aerodynamic and optimization data of ASTROS.

CAP–TSD requires mode shapes and streamwise slopes of mode shapes on aerodynamic grids, whereas ASTROS calculates them at the center of aerodynamic boxes. The transformation from aerodynamic box centers to grids is done by extrapolating the mode shapes and streamwise slopes values at the trailing edge and tip chord using a Mathematica[18] program.

While deciding the aerodynamic grids, note that the mesh should be finer around the control surface for capturing the hinge line pressure spike. Otherwise, the mesh breaks due to discontinuities and high pressures at the hinge line. While using CAP–TSD for solving a static aeroelastic problem, structural damping should be very high. The value used for this purpose is 0.999. The airfoil coordinates along with its slopes in the streamwise direction are calculated from the airfoil equations.

The iteration history for each TSD equation solution has to be checked for proper convergence. For the same convergence tolerance, the number of TSD equation iterations needed increases with the increase in dynamic pressure. For calculating the stability derivative C_{m_p}, the finite difference step size on roll rate used is 1.0 deg/s and its validity is checked by using a step size of 0.1 deg/s.

Design variable linking is used for reducing the hundreds of structural size variables to a small number (preferably below 10) so that design of experiments methods can be applied. However, shape linking cannot be used because the independent variables in shape linking are mostly coefficients of polynomials and thereby have no limit to the minimum or maximum values it can take. However, the response surface methods need the bounds on the independent variables to fix the design space. Thus, physical linking is used taking into account symmetry, manufacturing conditions, and any previous engineering information about the variation of thicknesses. For all of the DOE procedures, SAS,[19] a statistical software, is used. Statistical model evaluation parameters are checked before using the response surface approximation for prediction and optimization.

Intermediate Complexity Wing (ICW) Model

The intermediate complexity wing (ICW) finite element model, which is included as an example with ASTROS license, is used for the improved roll maneuverability design. The structural and aerodynamic model is shown in Fig. 2. The structure has three spars and eight ribs with concentrated masses throughout the structure. This is a tapered wing with a sweep angle of 26.8 deg and an aspect ratio of 2.33. The wing has a root chord of 48 in., tip chord of 29.33 in., and a semispan of 90 in. The aerodynamic model is larger than the structural model with a root chord of 90 in., tip chord of 48 in., and semispan of 108 in. Figure 3 shows the structural and aerodynamic models superimposed. The control surface used is an inboard trailing-edge flaperon. The flaperon has a spanwise length of 76.8 in. and chordwise width of 17.1 in. The airfoil is a symmetric NACA airfoil with 4% thickness. The finite difference mesh on the physical wing has 45 chordwise divisions and 33 spanwise divisions. The total finite difference grid extends from 10 chordlengths (1 chordlength = 90 in.) before the leading edge to 20 chordlengths after the leading edge in the chordwise direction and about 3.8 chordlengths from the tip chord in the spanwise direction and from 5 chordlengths up to 5 chordlengths down in the vertical direction. The computational mesh is a 96 × 50 × 70 (total 336,000) grid. The sweep angle of the control surface is 15 deg.

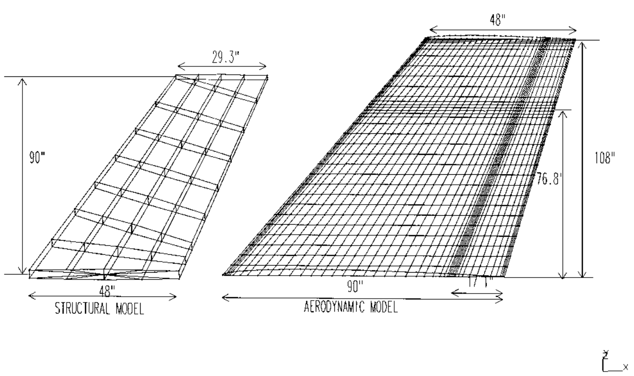

Fig. 2 ICW structural and aerodynamic model.

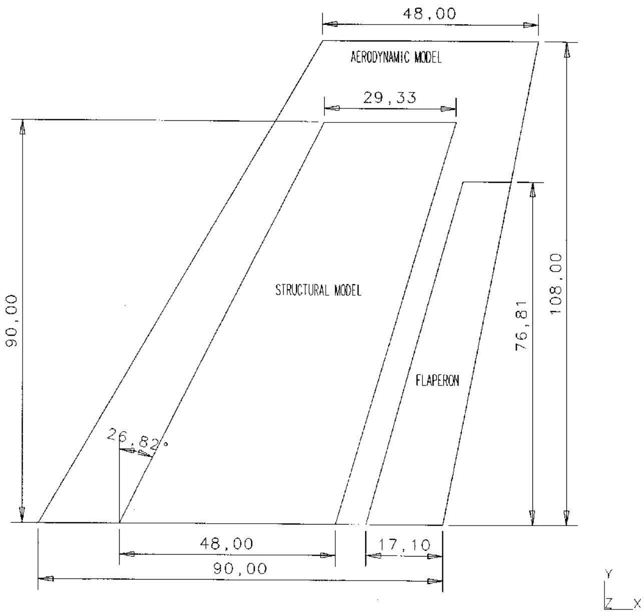

Fig. 3 ICW superimposed structural and aerodynamic dimensions.

Subsonic Analysis: 0.8 Mach

Performing the CAP–TSD and ASTROS analyses at varying dynamic pressures determines the roll rates and the control surface effectiveness. The variation of roll rates with dynamic pressures is plotted in Fig. 4. From Fig. 4, the roll rates for the ICW follow a similar trend in both ASTROS and CAP–TSD. Furthermore, it can be observed that the roll rates match more accurately at higher dynamic pressures as reversal is approaching.

The differences in results are attributed to the aerodynamic prediction procedures between CAP–TSD and ASTROS. Notably, ASTROS uses panel prediction techniques, where as the CAP–TSD is a time-integration procedure of finite difference differentiated equations. One is a panel method, the other is a CFD procedure.

The emphasis of this research is the preliminary design of air vehicle structures in the transonic regime using MDO and integration of higher fidelity aerodynamic analysis instead of panel methods in the design environment.

Transonic Analysis: 0.94 Mach

At 0.94 Mach, on studying the roll rate and ϵ_{cs} variation with dynamic pressure, it is observed that there is no significant change in the trends by changing from subsonic to transonic Mach number, even though there is a significant change in the magnitudes. A linear analysis in ASTROS at 0.94 Mach and a nonlinear analysis in CAP–TSD at the same 0.94 Mach are compared in Fig. 5. ASTROS predicted a reversal dynamic pressure of 60 lbf/in.^{2}, whereas CAP–TSD predicted 50 lbf/in.^{2}. Moreover, ASTROS always predicted higher control surface effectiveness than CAP–TSD with a maximum difference of about 40% at 30 lbf/in.^{2}. Thus, linear analysis

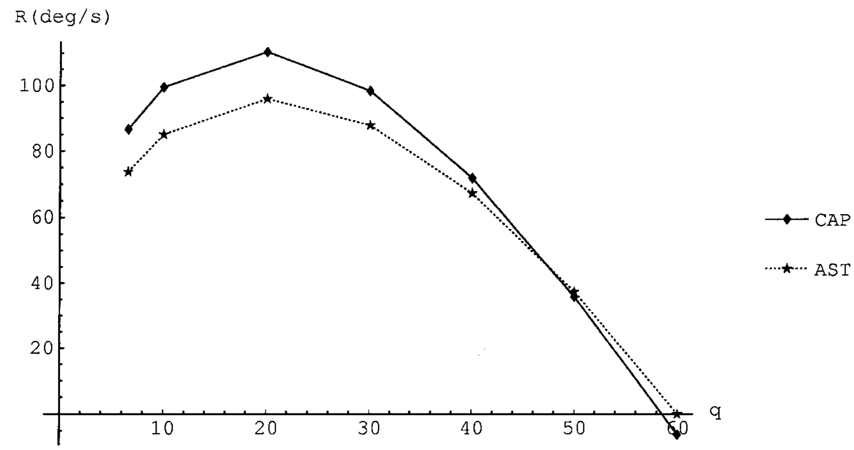

Fig. 4 ICW roll rate variation with q at 0.8 Mach.

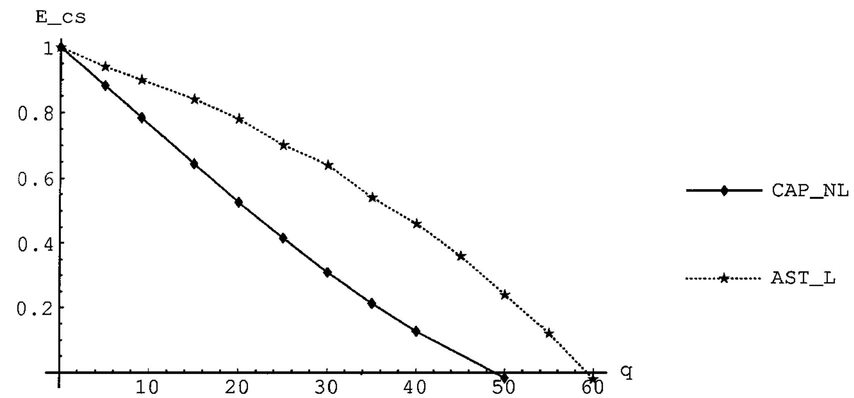

Fig. 5 ICW ϵ_{cs} variation with q at 0.94 Mach.

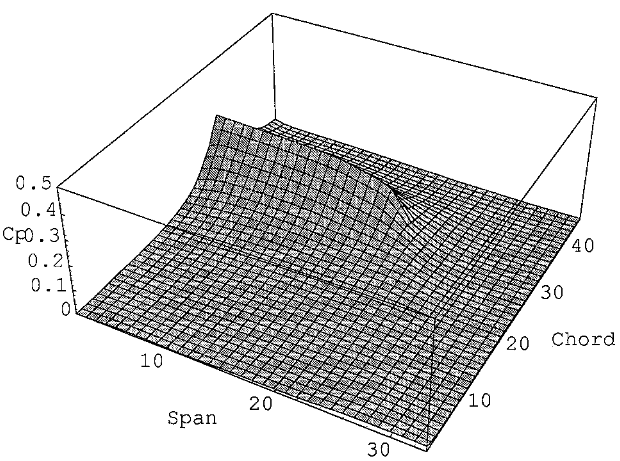

Fig. 6 CAP–TSD C_p for subsonic analysis showing hinge line pressure spike.

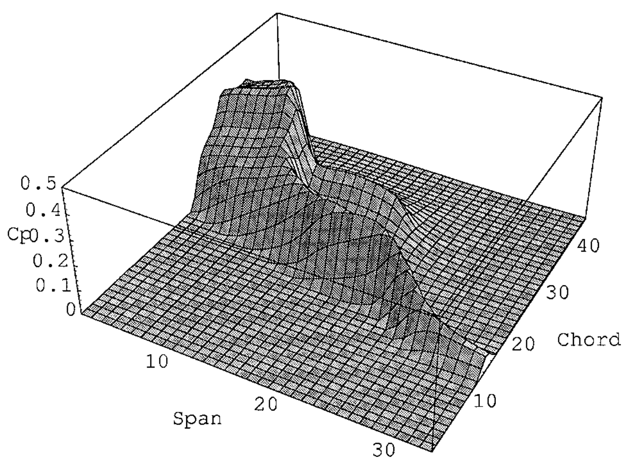

Fig. 7 CAP–TSD C_p for transonic analysis showing shocks and hinge line pressure spike.

is on the nonconservative side predicting higher control surface effectiveness and, consequently, higher reversal dynamic pressures than the actual nonlinear analysis. Hence, the designs based on linear aerodynamics in the transonic regime are nonconservative. This necessitates the incorporation of higher fidelity nonlinear aerodynamics in the preliminary design of transonic aircraft structures.

To determine whether the shock waves are captured by the TSD theory, the aerodynamic pressures ($Cp = Cp_{\text{upper surface}} - Cp_{\text{lower surface}}$) from a linear and a nonlinear analysis in CAP–TSD are plotted in Figs. 6 and 7. From Figs. 6 and 7, the presence of shock waves in a nonlinear analysis is clearly seen. The hinge line pressures in the linear Cp plot is not as high of magnitude as of shock Cp because the scale of Cp in each plot is different. The aerodynamic Cp obtained from a linear CAP–TSD analysis at 0.94 Mach is studied, and its profile is found to be similar to linear subsonic Cp except for a higher magnitude at the 0.94 Mach.

Response Surface Approximation of Control Surface Effectiveness

Because the nonlinear analysis is capturing shocks and the ϵ_{cs} calculation is reasonable, it is imperative to proceed with the optimization. For the ICW model, the number of structural elements is 158 (64 skin elements, 23 spar elements, 32 rib elements, and 39 post elements). Thus, there are potentially 158 local design variables with each element's thickness (of skins, spars, ribs) and cross-sectional areas (of posts) to be designed. Upon physical linking, the number of independent variables is reduced to eight. Symmetry is used between the upper and lower skins. The whole skins are divided into four columns with eight elements in each column. Each column is assigned to a single global variable, and all of the elements in a column are assumed to have the same thickness. All of the spars' elements are linked to two global variables depending on whether they are nearest to the root chord or tip chord. All rib elements are assigned to a single global variable, and all post areas are assigned to another global variable. The eight global variables are as follows: thickness of skins at root chord A, thickness of skins at left of midchord B, thickness of skins at right of midchord C, thickness of skins at tip chord D, thickness of spars at root chord half E, thickness of spars at tip chord half F, thickness of all rib elements G, and areas of all post elements H.

The thicknesses are allowed to vary from a lower limit of 0.05 in. to an upper limit of 1.0 in. Nevertheless, eight is a large number of independent variables for response surface because it requires 273 CAP–TSD analyses (using central composite design), which is computationally expensive. Conducting 2^{8-4} fractional factorial design with 16 CAP–TSD analyses helps in determining which of the eight variables are statistically significant. In the ICW case, it is found that the four global design variables A, B, C (skin thickness toward root chord), and E (spars near the root chord) are significant. Dropping the other four variables, the response surface is constructed by conducting 25 CAP–TSD analyses. The structural dimensions for these 25 points are chosen using D-optimality criteria from a possible selection of 625 points. The statistically insignificant variables (D, F, G, and H) are fixed at their lower limit of 0.05 in. in building the response surface. This is done to get a conservative approximation from the response surface. The approximate quadratic equation for control surface effectiveness is

$$\begin{aligned}\epsilon_{cs} = {} & 0.143594 + 0.700856A + 0.852593B + 0.388251C \\ & + 0.278785E - 0.419794A^2 - 0.005254B \times A \\ & - 0.517092B^2 + 0.004079C \times A - 0.026992C \times B \\ & - 0.238259C^2 - 0.043344E \times A - 0.013724E \times B \\ & + 0.013986E \times C - 0.161005E^2 \qquad (17)\end{aligned}$$

Design Optimization and Comparative Studies

In MDO of the aircraft wing, Eq. (17) is used to represent the approximate control surface effectiveness instead of the exact CAP–TSD simulations at every iteration. The Mach number is 0.94, and the matched dynamic pressure is 9.0889 lbf/in.^{2}. The constraints considered from other disciplines include fundamental frequency ($\omega_1 \geq 1.3$ Hz), displacement at the tip of the wing ($\delta \leq 8.0$ in.), and stresses in all of the elements ($\sigma \leq \sigma_{allow}$). The stress limits are 1.295×10^5 psi in tension, compression, and shear for skins. For spars, ribs, and posts, the stress limits are 6.7×10^4 psi in tension, 5.7×10^4 psi in compression, and 3.9×10^4 psi in shear. All eight design variables are used even though some of them are insignificant from the control effectiveness point of view because they could be significant for other disciplines.

Initially optimization is done with stress, displacement, and frequency constraints and without ϵ_{cs} constraint. At the optimum point (shown in Table 1, column 1), ASTROS predicted control surface effectiveness of 0.84 using linear aerodynamics. This is a displacement-driven design, and also stresses in the trailing-edge root spar are at the limit. When ϵ_{cs} constraint (as calculated by ASTROS from linear aerodynamics) is added and optimized (shown in Table 1, column 2), the weight increased by 5 lb from 213.43 to 218.42 lb, and the displacement and frequency constraints are no longer active although the stresses in the root skins and root spar are at the limit. However, if a nonlinear CAP–TSD analysis is done at these structural sizes, the actual ϵ_{cs} is 0.6131. This is 24% less than the linear aerodynamics predicted value. This is a large design violation for roll performance.

To improve the CAP–TSD nonlinear based ϵ_{cs} by 15% or so, the approximate equation of ϵ_{cs} [obtained using nonlinear aerodynamics Eq. (17)] is used ($\epsilon_{cs} \geq 0.75$), and optimization is performed (shown in Table 1, column 3), the design has a weight of 273.15 lb, which is about 55 lb heavier than the earlier design. The actual value of ϵ_{cs} as found from CAP–TSD analysis is 0.7910 (an improvement of 18%).

At the optimum designs obtained using linear and nonlinear aerodynamics (Table 1, columns 2 and 3), a series of nonlinear CAP–TSD analysis at 0.94 Mach are conducted with increasing the dynamic pressure. The reversal dynamic pressures obtained (Fig. 8) are 30 lbf/in.^{2} for the linear aerodynamics-based design and 60 lbf/in.^{2} for the nonlinear-aerodynamics-based structure. The two optimum designs are two different structures with

Table 1 Comparison of optimum designs

Parameter	S + D + F[a] design	ϵ_{cs} Linear aero S + D + F[a] design	ϵ_{cs} Nonlinear aero S + D + F[a] design
Constraints			
$\sigma \leq \sigma_{crit}$	Trailing edge root spar[b]	Root skin and root spar	None active
$\delta \leq 8.0$ in.	8.0[b]	7.84[c]	4.06[c]
$\omega \geq 1.3$ Hz	1.4[c]	1.32[c]	1.604[c]
ϵ_{cs}	No constraint	0.86[b]	0.75 on rsm[b]
Computed values			
ϵ_{cs} (ASTROS)	0.84	0.86	0.92
ϵ_{cs} (CAP–TSD)	0.5875	0.6131	0.7910
Objective weight, lb	213.43	218.42	273.15
Design variables 0.05–1.0 in.			
Root skins	0.131	0.097	0.210
Midskins (left)	0.115	0.127	0.206
Midskins (right)	0.081	0.114	0.212
Tip skins	0.050	0.088	0.229
Root spars	0.102	0.106	0.227
Tip spars	0.050	0.075	0.237
Ribs	0.050	0.050	0.050
Posts	0.050	0.050	0.050

[a]Stress plus displacement plus frequency. [b]Active. [c]Not active.

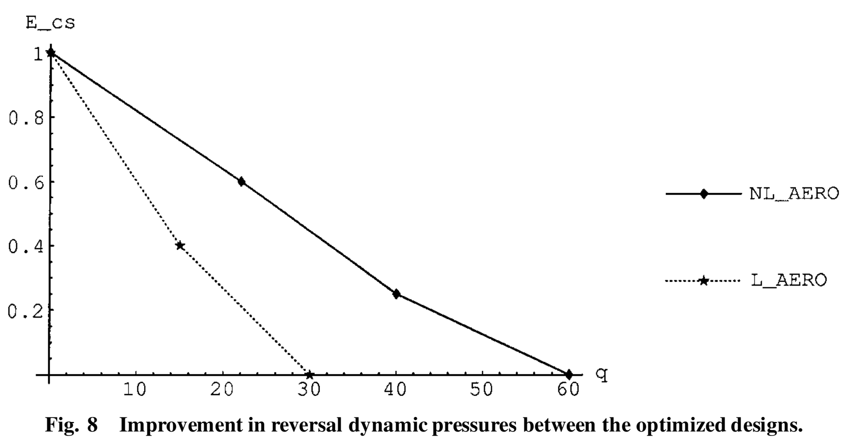

Fig. 8 Improvement in reversal dynamic pressures between the optimized designs.

Table 2 Material addition from linear to nonlinear aerodynamics design

Design variable	% Weight increase
Root skins	11.9
Midskins (left)	9.1
Midskins (right)	9.9
Tip skins	8.7
Root spars	7.9
Tip spars	7.1
Ribs	0.0
Posts	0.0

the nonlinear-aerodynamics-based design being heavier and having higher control surface effectiveness.

The design variables obtained from the linear aerodynamics design and nonlinear aerodynamics design are shown in Table 1. The material distribution indicating the percentage of the additional weight increase in the global variables is shown in Table 2. From Table 2, it is can be observed that the skin elements, especially those nearest to the wing root, have a significant influence, whereas ribs and posts have the least influence the on roll performance.

Conclusions

Designing of aircraft structures in the transonic regime for aeroelastic performances requires high-fidelity nonlinear aerodynamic flow solvers. Furthermore, to design in the preliminary design environment, efficiency and less computational cost are also required. CAP–TSD, which employs the TSD theory, is an appropriate nonlinear aerodynamic solver that satisfies the efficiency and accuracy requirements of preliminary design. The limitation of using the TSD theory is that it is not applicable for extreme flight conditions involving high nonlinearities. Using linear aerodynamics in the transonic region is found to be nonconservative because they predict significantly higher performance than the actual value obtained from nonlinear aerodynamics.

The nongradient-based DOE methodology is found to be a good design tool leading to improved designs. The fractional factorial design method of selecting significant variables reduces significantly the number of experiments needed for response surface approximation. The response surface methods, if applied judiciously, leads to adequately accurate approximations that can be used in design optimization. Roll performance improvements using DOE methodology is a good practical choice in the case of less design variables, lack of sensitivity information, and expensive analysis. Though DOE method has a broad applicability for approximating any function in terms of design variables, the major limitation is the excessive number of experiments needed even for a small number of design variables (above five). It is to overcome this limitation that sensitivity-based methods of optimization have to be considered if the function gradient information is available.

Acknowledgments

The authors acknowledge the sponsorship of Air Force Office of Scientific Research (AFOSR) through Grant F49620-98-1-0354. Brian Sanders was the Program Manager at AFOSR and Phil Beran was the Task Leader at the Air Force Research Laboratories. The authors acknowledge NASA Langley Research Center for providing the CAP–TSD program for this research.

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